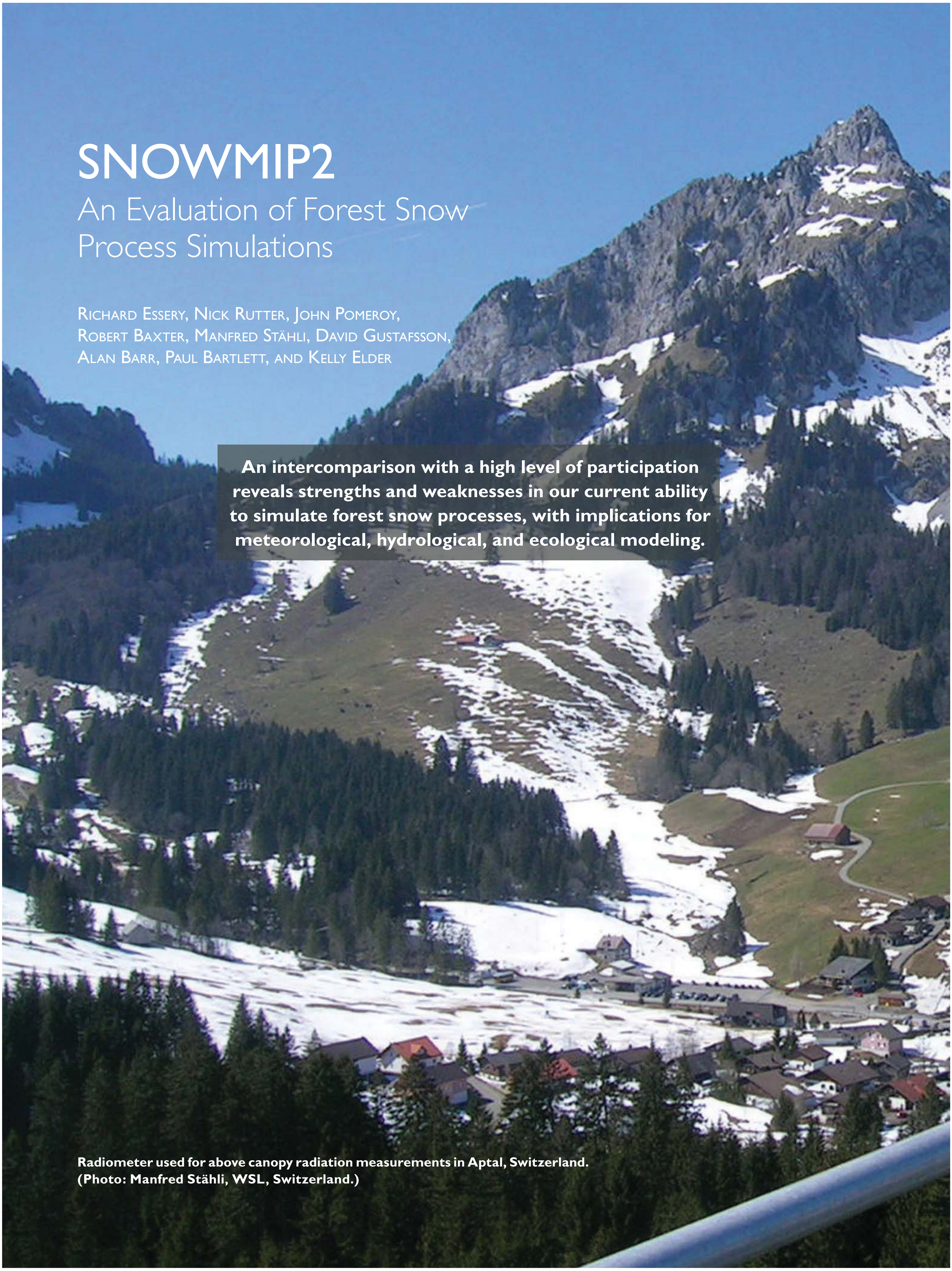

SNOWMIP2

An Evaluation of Forest Snow Process Simulations

Richard Essery, Nick Rutter, John Pomeroy, Robert Baxter, Manfred Stähli, David Gustafsson, Alan Barr, Paul Bartlett, and Kelly Elder

An intercomparison with a high level of participation reveals strengths and weaknesses in our current ability to simulate forest snow processes, with implications for meteorological, hydrological, and ecological modeling.

Radiometer used for above canopy radiation measurements in Aptal, Switzerland. (Photo: Manfred Stähli, WSL, Switzerland.)

Models of terrestrial snow cover, or snow modules within land surface models, are used in many meteorological, hydrological, and ecological applications. Such models were developed first, and have achieved their greatest sophistication, for snow in open areas; however, huge tracts of the Northern Hemisphere both have seasonal snow cover and are forested (Fig. 1). Forests have large influences on snow dynamics, and many snow models have been developed or modified in recent years to include vegetation canopies (e.g., Hellström 2000, Koivusalo and Kokkonen 2002; Niu and Yang 2004; Bartlett et al. 2006). Despite this, snow processes have been identified as an area of continuing weakness in global land surface models (Dirmeyer et al. 2006), and the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report concluded that "Large discrepancies remain in albedo for forested areas under snowy conditions, due to difficulties in determining the extent of masking of snow by vegetation" in climate models (Randall et al. 2007; Roesch 2006). This paper presents an overview of the results obtained in an intercomparison project evaluating the performance of a large number of models at several forested and open locations with seasonal snow cover.

With only limited observations available to evaluate the wide range of state variables and fluxes simulated by land surface models, ▶

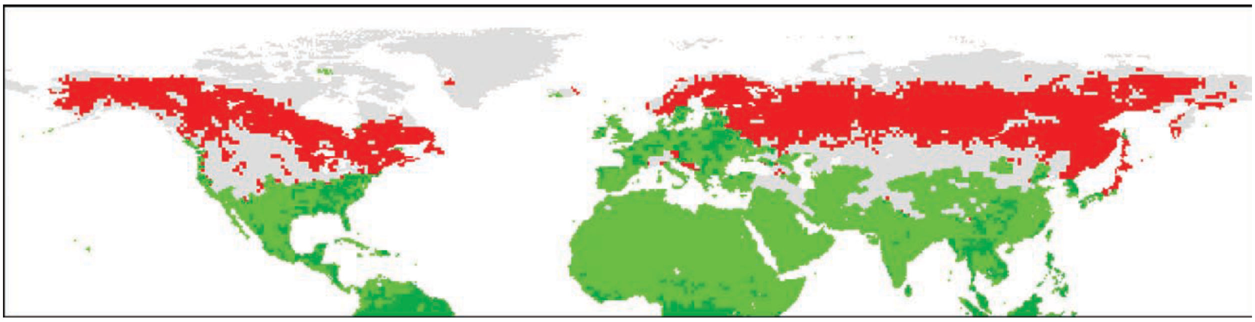

Fig. 1. Northern Hemisphere snow cover (Jan 2005) and forests. Snow-free forests (dark green), unforested areas with snow cover (gray), and forests with snow cover (red) are shown. Data are from the National Snow and Ice Data Center (NSIDC) Equal-Area Scalable Earth Grid (EASE-Grid) snow cover product (Armstrong and Brodzik 2005) and the University of Maryland global land cover classification (Hansen et al. 1998).

there have been many attempts to gain an improved understanding of model performance through intercomparison projects. The most significant initiative of this kind has been the Project for the Intercomparison of Land-surface Parameterisation Schemes (PILPS; Henderson-Sellers et al. 1995). Two of the PILPS phases to date have involved sites with seasonal snow cover: PILPS 2d for grassland at Valdai, Russia (Slater et al. 2001), and PILPS 2e for the partially forested catchments of the Torne and Kalix Rivers in northern Scandinavia (Bowling et al. 2003). Whereas PILPS concentrates on evaluating land surface schemes used in atmospheric models, the Snow Model Intercomparison Project (SnowMIP) deals specifically with snow processes and aims to involve models with a wider range of complexities and applications, including hydrological models, land surface schemes, and sophisticated snow physics models. In the first phase of SnowMIP, simulations of snow-water equivalent (SWE) and surface energy budgets for one or more winters were compared with observations from sites with short vegetation fully buried by snow (Etchevers et al. 2004); model complexity was found to have an important role in net longwave radiation calculations, but not in the simulated absorption of shortwave radiation by snow surfaces. More recently, Feng et al. (2008) have investigated the impact of model complexity on snow simulations by five models, including forest cover.

To evaluate how well current models can simulate snow processes in forests, SnowMIP2 was commissioned as a working group of the International Commission for Snow and Ice (now the International Association of Cryospheric Sciences) in 2003 and was subsequently also adopted as an activity of the Global Land/Atmosphere System Study (GLASS). There was a remarkable response to the call for participants in SnowMIP2: initial interest was registered for 41 models, and results from 33 models were returned by the final deadline in March 2007, compared with the 21 model returns in PILPS 2d and 2e and the 24 in SnowMIP1. This alone shows progress, in that there are now a large number of models that can perform the complex simulations required for SnowMIP2. The participating models are listed in Table 1; they include an operational hydrology model (SNOW-17), a snow physics model (SNOWPACK), several hydrological models [e.g., Cold Region Hydrological Model (CRHM) and Variable Infiltration Capacity (VIC)], and several GCM land surface schemes [e.g., Canadian Land Surface Scheme (CLASS) and Interactions Between Soil, Biosphere, and Atmosphere (ISBA)] run by participants at institu-

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The abstract for this article can be found in this issue, following the table of contents.

DOI:10.1175/2009BAMS2629.1

In final form 10 March 2009

tions in 11 countries. The complexity of the models in representing canopy processes ranges from SNOW-17 (Anderson 1976), which includes the influence of the canopy merely by reducing the snowfall reaching the ground, to Advanced Canopy–Atmosphere–Soil Algorithm (ACASA; Pyles et al. 2000), which used a 10-layer canopy model for the SnowMIP2 simulations. In the following sections, we present an overview of forest snow processes and how they are modeled, describe the procedures and data used in SnowMIP2, and show comparisons of model results with simulations of snow mass, albedo, surface temperature, and soil temperature. Implications for meteorological, hydrological, and ecological modeling are drawn in the conclusions.

FOREST SNOW PROCESSES. Because dense forest canopies remain dark, are aerodynamically rough, and can have surface temperatures exceeding 0°C, even while there is snow on the ground, the presence or absence of forests has profound influences on the energy balance of snow-covered landscapes and the development of atmospheric boundary layers. Large upward sensible heat fluxes from dry canopies in spring lead to deep daytime boundary layers over forests (Betts et al. 2001), compared with shallow stable boundary layers over melting snow. Viterbo and Betts (1999) found that a poor representation of albedos for forests with snow led to large cold biases in European Centre for Medium-Range Forecasts (ECMWF) forecasts prior to the introduction of a new snow scheme. Many studies have shown that the masking of snow albedo by boreal forests strongly influences simulated climates (Thomas and Rowntree 1992; Chalita and Le Treut 1994; Gallimore and Kutzbach 1996; Douville and Royer 1997; Betts 2000; Renssen et al. 2003), but these have generally been simple sensitivity studies involving the complete removal of forests. In reality, forest responses to changing temperatures, precipitation, management practices, and disturbances, such as fire and insect outbreaks, are complex. With dynamic vegetation models being increasingly used within climate change simulations, it is increasingly important that land surface schemes should be able to represent the influence of snow on biophysical processes.

Table 1. Models participating in SnowMIP2.

Model	Participant	Affiliation
2LM	Takeshi Yamazaki	IORGC/JAMSTEC
ACASA	R. David Pyles	University of California, Davis
CLASS	Paul Bartlett	Environment Canada
CLM2-TOP	Hua Su	University of Texas at Austin
CLM3	Reto Stöckli	MeteoSwiss
COLA-SSiB	Xia Feng	COLA
CoupModel	David Gustafsson	Royal Institute of Technology KTH
CRHM	Chad Ellis	University of Saskatchewan
ESCIMO	Ulrich Strasser	University of Munich
ISBA-D95	Eric Martin	CNRM-GAME (Météo-France, CNRS)
ISBA-ES	Eric Martin	CNRM-GAME (Météo-France, CNRS)
JULES	Andy Wiltshire	Met Office
MAPS	Tanya Smirnova	NOAA/ESRL/GSD
MATSIRO	Kumi Takata	FRCGC/JAMSTEC
MOSES	Richard Essery	University of Edinburgh
Noah LSM	Victor Koren	NOAA
RCA	Patrick Samuelsson	SMHI
SNOW-17	Victor Koren	NOAA/NWS/OHD
SAST	Wei-Ping Li	National Climate Centre
SiB 2.5	Reto Stöckli	MeteoSwiss
SiB 3.0	Ian Baker	Colorado State University
SiBUC	Kenji Tanaka	Kyoto University
SNOWCAN	Mel Sandells	ESSC, University of Reading
SNOWPACK	Tobias Jonas	SLF
SPONSOR	Andrey Shmakin	Institute of Geography, Russian Academy of Sciences
SRGM	Alexander Gelfan	Water Problems Institute, Russian Academy of Sciences
SSiB3	Yonkgang Xue	University of California, Los Angeles
SWAP	Yeugeniy Gusev	Water Problems Institute, Russian Academy of Sciences
TESSEL	Pedro Viterbo	Instituto de Meteorologia
UEB	Charlie Luce	U.S. Department of Agriculture
UEBMOD	Rob Hellström	Bridgewater State University
VEG3D	Gerd Schädler	Karlsruhe Research Centre
VIC	Kostas Andreadis	University of Washington

Forests play a vital role in fluxes of carbon between the land surface and the atmosphere, particularly in the Northern Hemisphere. Carbon sink strength is closely linked to the growing season length for seasonally snow-covered ecosystems, with earlier snowmelt resulting in a longer growing season and greater carbon uptake (Lafleur and Humphreys 2007; Groendahl et al. 2007). This increase in uptake may depend to a large extent on the amount of recharge of plant-available water deep in the soil profile, especially when growing-season moisture limits productivity (Kljun et al. 2007; Henne et al. 2007; and references therein). The freezing and thawing of soils affects the turnover of soil organic matter and thus affects losses of both carbon and nitrogen from soils (Matzner and Borken 2008). Soil processes are of particular importance at low temperatures because of the greater temperature sensitivity. Soil respiration and mineralization of nitrogen have recently been shown to be substantial over the winter period (e.g., Grogan et al. 2004; Monson et al. 2006). Adequate representation of such biophysical processes in estimating annual carbon fluxes remains a key goal in ecological modeling. Snow cover protects both forest understorey species and tree seedlings from cold winter temperatures, and hence snow plays a role in determining forest canopy recruitment and structure. Horizontal and vertical canopy structure within a forest stand affects the amount and variability of snow accumulation and melt (Pomeroy et al. 2002). Recent results have predicted that variations in snow cover resulting from variations in forest interception and topography will be enhanced by climate warming, resulting in increased spatial variability in soil temperatures (Mellander et al. 2007). The fate of snow following deposition is thus of critical importance for both short- and long-term ecological processes in boreal forest ecosystems.

Wind-blown snow may be deposited around forest edges, collecting deeper snow than in open areas, but snow accumulation will generally be less under an extensive canopy than in open areas receiving the same snowfall because of the interception and sublimation of canopy snow. Canopies can strongly modify surface energy fluxes and melt rates compared with open areas. Forest snow processes thus have an inordinate role in governing streamflow, wetland recharge, and soil moisture in forested basins. Soils are often frozen or saturated at the time of snowmelt, resulting in large runoff fractions. For instance, the middle and upper elevations of the Rocky Mountains have deep seasonal snowpacks and vegetation cover that is dominated by evergreen coniferous forests. Goodell (1966) calculated that 90% of the annual runoff from above 2740 m in the Colorado Rockies is derived from snowmelt. Spring snowmelt runoff provides more than 70% of the streamflow from the Rockies in the United States and Canada, and is associated with instantaneous discharges that are up to 100 times greater than mean low flow (Hauer et al. 1997; Stewart et al. 2004). In the boreal forest the annual peak runoff events, maximum soil moisture levels, and seasonal wetland recharge are associated with spring snowmelt (Pomeroy and Granger 1997; Elliot et al. 1998). From 40% to 60% of annual streamflow in the boreal and northern hardwood forests of Canada is derived from snowmelt (Hetherington 1987).

Forest vegetation is subject to succession, management, disease, and fire. There have been several basin-scale experimental studies to examine the role of changing forest cover on snowmelt. In general, surface vegetation removal has the potential to increase both snow accumulation and melt rates, and hence to increase the magnitude and frequency of peak streamflows in snowmelt-dominated mountainous watersheds (Troendle and King 1985; Troendle and Leaf 1981; Pomeroy and Gray 1995). Boreal forest cover removal has been associated with an almost doubling of snow accumulation (Pomeroy et al. 1998) and tripling of snowmelt rates (Pomeroy and Granger 1997), followed by 24%–75% increases in snowmelt runoff at the basin scale (Hetherington 1987). Conversely, afforestation in upland Scotland has reduced discharge from catchments where snowmelt can contribute to winter streamflow (Calder 1990). There is currently great concern about pine mortality caused by outbreaks of the mountain pine beetle in North America (Aukema et al. 2006; Kurz et al. 2008); this has affected more than 7 million ha in British Columbia alone. Potts (1984) found a 15% increase in basin water yield and a 3-week advance in the timing of spring peak flow associated with a relatively small (35%) pine beetle infestation in a high mountain forested catchment. Salvage logging may exacerbate the impact on snow hydrology, with much greater changes to snowmelt rates following the removal of dead trees (Boon 2007). Remote sensing of snow properties is important for the assimilation in hydrological and numerical weather prediction models (Drusch et al. 2004), evaluation of climate models (Frei et al. 2003), and detection of climate trends (Dye 2002), but exposed vegetation complicates the signatures of snow-covered ground in both visible and microwave bands (Klein et al. 1998; Chang et al. 1996; Pullianen et al. 2001). Conversely, the presence of snow complicates retrievals of vegetation indices (Robin et al. 2007). Algorithms for satellite products often include simple representations of canopy radiative transfer, but forest canopies remain one of the largest sources of uncertainty in the remote sensing of snow (Vikhamar and Solberg 2002). For dense forests, snow cover could be mapped by remote sensing of snow in canopy gaps, provided that relationships between snow in the open and under canopies can be predicted.

FOREST SNOW PROCESS MODELS. Conceptual models with various degrees of sophistication are often used for operational snowmelt runoff forecasting (WMO 1986). Such models can be run with limited driving data (e.g., snowfall and air temperature alone) but typically require calibration against observations for a particular location, catchment, or region. Calibration is not possible for ungauged catchments or future conditions of changing climate or land cover, and physical process models are expected to be more reliable. These are based on conservation equations that predict changes in state variables such as temperature and liquid or solid water storage in response to divergences in energy and mass fluxes. The conservation equations are coupled by water phase change terms and exchanges between control volumes. Writing out conservation equations for control volumes encompassing the canopy, the snowpack, and the ground is straightforward; the difficulty lies, of course, in parametrizing the fluxes as functions of state variables, meteorological variables, and well-defined, measurable surface characteristics. The presence of an overlying vegetation canopy influences every flux term in the surface mass and energy balances of a snowpack. Forest environments have high spatial variability over wide scale ranges, but most models are one-dimensional, aiming to represent area-average state variables and vertical fluxes.

Snow falling on a forest is partitioned into interception by the canopy and throughfall to the ground. As the intercepted snow load increases, the interception efficiency increases because of snow bridging between canopy elements but decreases due to bending of branches under the load. Models generally parameterize the maximum load that can be held by a canopy as a function of leaf area index. Canopy capacities can be much greater for snow than for liquid water, although this is not always reflected in model parameterizations. Interception calculations in many of the SnowMIP2 models are based on the Hedstrom and Pomeroy (1998) scheme, which incorporates estimates of canopy snow capacity from Schmidt and Gluns (1991); however, models differ in how they implement this scheme (Bartlett et al. 2006). Snow can be removed from canopies by direct unloading, drip of meltwater, and sublimation. Unloading rates are functions of temperature and wind speed in some models (Roesch et al. 2001; Niu and Yang 2004).

Forest canopies shade underlying snow from both direct and diffuse solar radiation. Sophisticated models of canopy radiative transfer have been developed and evaluated by intercomparison (Pinty et al. 2004), but the data and computational requirements of these models are too high for use in land surface schemes. Instead, many models use variants of Beer's law, which provides a simple bulk canopy transmissivity with an exponential dependence on leaf area index (Ross 1981). A single transmissivity may be used, or separate transmissivities may be calculated for visible and near-infrared radiation in direct and diffuse beams; these components are rarely available separately from observations, so they have to be parametrized if used. Other models use a two-stream approximation (Dickinson 1983; Sellers 1985), which allows for scattering and multiple reflections by the canopy between vertical upward and downward radiative fluxes. Yang et al. (2001) adapted the two-stream approximation to allow for transmission through gaps between trees.

Longwave radiation beneath canopies is increased compared with open areas because emissivities are greater for canopy elements than for the atmosphere and the canopy can be substantially warmer than the air due to absorption of solar radiation (Harding and Pomeroy 1996). For high-albedo snow and dense canopies, increased longwave radiation can even outweigh decreased shortwave radiation in the net radiation at the snow surface (Sicart et al. 2004). Observations and modeling of subcanopy radiation have received rather less attention for longwave than shortwave radiation. Incoming longwave radiation is generally parametrized as the sum of radiation from the canopy and from the sky through canopy gaps using a sky-view fraction that, again, depends on leaf area index.

Turbulent transfers of heat and moisture below forest canopies and above snowpacks involve complex processes that have to be modeled with simple parametrizations. Almost all of the SnowMIP2 models use first-order closure, although one uses a higher-order turbulence scheme and a multilayer canopy model (Pyles et al. 2000). Surface exchange coefficients may be obtained by integration of eddy diffusivities through the canopy (Niu and Yang 2004) or by an empirical reduction of wind speed (Gelfan et al. 2004;

Table 2. Characteristics of sites used in SnowMIP2.			
	Alptal	**BERMS**	**Fraser Experimental Forest**
Location	47°3′N, 8°43′E	53°55′N, 104°42′W	39°53′N, 105°53′W
Elevation	1185 m	579 m	2820 m
Forest type	Spruce and fir	Pine	Pine, spruce, and fur
Tree height	~35 m	12–15 m	~27 m
Leaf area index	2.5	1.66	3
Snow-free albedo	0.11 (forest) 0.19 (open)	0.11 (forest) 0.16 (open)	0.05 (forest) 0.1 (open)

Tribbeck et al. 2004). Some models adjust exchange coefficients according to subcanopy stability (Niu and Yang 2004), but others do not.

FORCING AND EVALUATION DATA. Energy balance models generally require inputs of shortwave and longwave radiation, snowfall and rainfall rates, wind speed, air temperature, humidity, and pressure on time steps of 3 h or shorter. These inputs may be provided by an atmospheric model or measurements. Automatic measurement of meteorological variables can be challenging in cold and snowy environments: anemometers may freeze, radiometers may be covered by snow, and the accurate measurement of solid precipitation is particularly difficult (Goodison et al. 1998). Model driving, initialization, and evaluation data for SnowMIP2 were collated from observations at five sites. At two of these sites (Histsujigaoka, Japan, and Hyytiälä, Finland), slightly different simulation procedures were followed; these sites are omitted from this discussion for simplicity but are included in a companion paper (Rutter et al. 2009). A common procedure was used for the three sites described in Table 2: Alptal in Switzerland, the Boreal Ecosystem Research and Monitoring Sites (BERMS) in Saskatchewan, Canada, and the Fraser Experimental Forest in Colorado. At each site, measurements were available from a forested plot and a nearby open plot with short vegetation (Fig. 2). Simulations were to be run for two complete winters at each plot. Initial soil temperature and moisture profiles were given, and SWE observations were provided for the first winter only at each of the forest plots to allow some model calibration; this was not compulsory, and calibration methods were not prescribed. Meteorological data were supplied as 30-min averages, interpolated from hourly measurements in some cases and gap filled if necessary.

Fig. 2. Photographs of the (left) open and (right) forested plots at (top) Alptal, (middle) BERMS, and (bottom) Fraser Experimental Forest.

The data were of unusual quality and completeness; longwave radiation, in particular, has often been parametrized in previous intercomparison projects (e.g., Slater et al. 2001; Bowling et al. 2003), but direct measurements were used for SnowMIP2. Measured total precipitation was corrected and partitioned by the data providers using separate techniques based on local knowledge for each site. The choice of threshold temperatures for partitioning total precipitation into snow and rain makes little difference for BERMS or the Fraser Experimental Forest, where most of the winter precipitation falls as snow at temperatures well below 0°C, but this introduces a large uncertainty for Alptal, where precipitation at near-freezing temperatures is common. Figure 3 shows 10-day averages of meteorological variables and cumulative snowfall for the two winters at each site. BERMS is the coldest, driest, and windiest of the sites, whereas Alptal is the warmest and wettest; the climate at Fraser Experimental Forest lies between these extremes, although it receives the most solar radiation because of its high elevation and low latitude. There is less difference in temperature between the sites in spring than in winter.

Stand characteristics provided for each forest plot were limited to forest type, canopy height, leaf area index, and snow-free albedo (Table 2), from which the modeling participants had to estimate undefined model parameters. More complete characterizations could be given for these research sites, but models often have to use large-scale vegetation maps with limited parameter sets.

Snow accumulation can have high spatial variability because of redistribution by wind in exposed areas and canopy interception in forests. Automatic instruments, such as ultrasonic depth gauges and snow pillows, give measurements over limited areas. SWE is often measured by a manual sampling of snow depth and mass at a number of points along a transect. Because this is a labor-intensive procedure, SWE data were only obtained for a few dates per winter at each of the SnowMIP2 sites.

MODEL RESULTS. The model outputs requested for SnowMIP2 were based on the widely used Assistance for Land Surface Modeling Activities (ALMA) data standard (Polcher et al. 2000), with some extensions to allow full characterization of the energy and mass balances of snow on the ground and intercepted in the canopy. The ALMA conventions require data to be exchanged in net cumulative distribution function (NetCDF) format, but either NetCDF or American Standard Code for Information Interchange (ASCII) outputs were allowed for SnowMIP2, because it was expected that several of the models would not have previously participated in formal intercomparison projects.

Figure 4 compares simulations of SWE with observations. For clarity, medians and interquartile ranges are shown for the models rather than individual results for every model. The observations consistently show lower maximum accumulation but later melt at the forest sites rather than the open

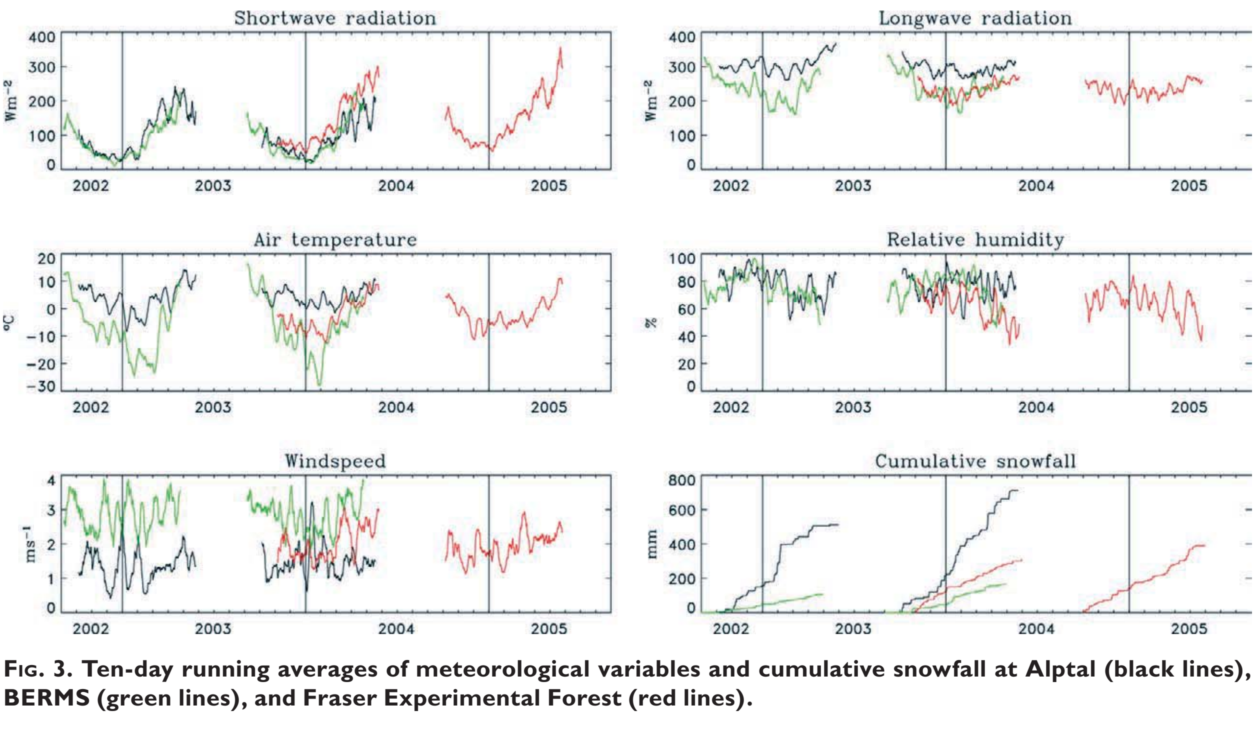

Fig. 3. Ten-day running averages of meteorological variables and cumulative snowfall at Alptal (black lines), BERMS (green lines), and Fraser Experimental Forest (red lines).

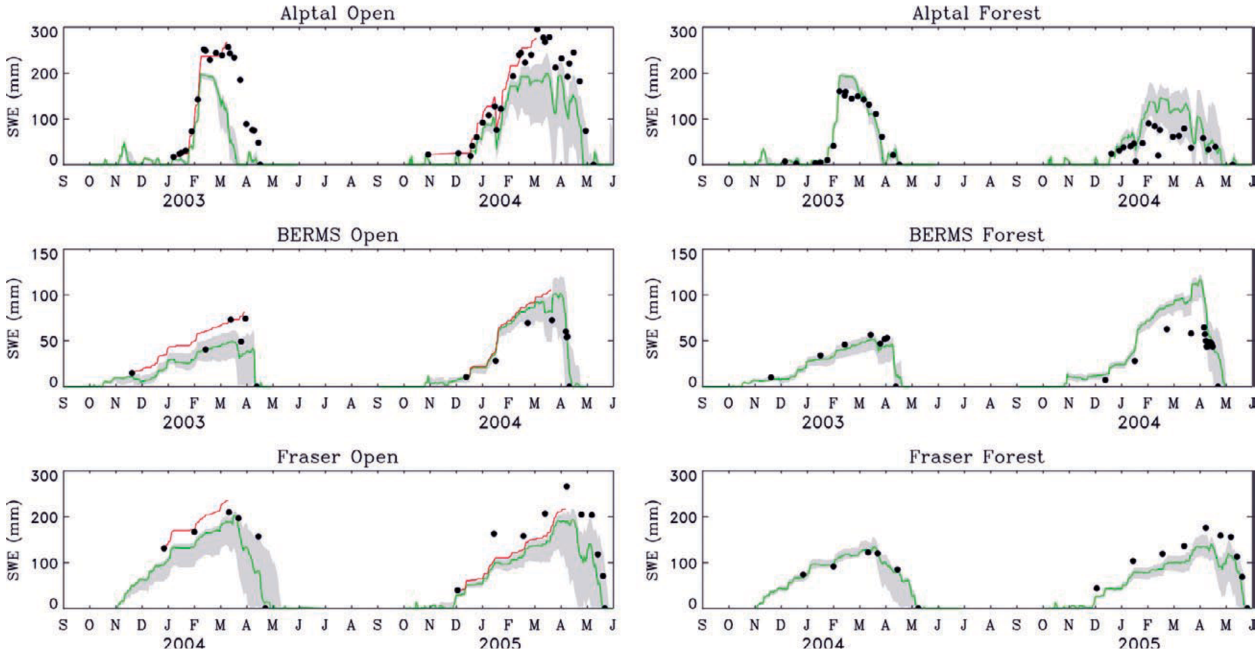

Fig. 4. Observed and modeled snow-water equivalent at open and forested sites. Observations (black dots), model medians (green lines), and interquartile ranges (gray bands) are shown. Red lines show cumulatve snowfall at open sites between the time of the first snow survey each winter and the time of maximum accumulation.

sites; differences are small for BERMS and particularly large for Alptal in 2004. On average, the models capture but underestimate the differences between forested and open sites. Differences between models are large, particularly for the warmer second winter at Alptal. Cumulative snowfall between the first survey date each winter and the time of maximum snow accumulation is also shown in Fig. 4 for the open sites to identify periods in which there may be inconsistencies between the driving and evaluation data. For Alptal, observations and models agree that snow falling in November and December 2002 and 2003 largely melted, but the total snowfall thereafter closely matches the maximum accumulation. Most of the models melt some of this snow, giving maximum accumulations that are less than those observed; increased snowfall in the driving data would improve the comparison between models and observations for the Alptal open plot, but would degrade model performance for the forest plot, where most models overestimate the maximum SWE. At BERMS, the snowfall matches the maximum SWE in early April 2003, but this is hard to reconcile with lower observations from two of the surveys. The cumulative snowfall exceeds the observed accumulation in 2003/04, and this is consistent with the trend for models to overestimate the observed SWE at both the open and forested BERMS plots in that winter. The first surveys of the winter at BERMS were made in November 2003 and December 2004, but photographs from an automatic camera show that there was snow on the ground in October of both years that largely melted before the development of persistent winter snow cover. Models differ in whether they do or do not melt this early snow; those that do not have a positive SWE bias "frozen in" for the winter. For Fraser Experimental Forest, snowfall matches accumulation for 2003/04 but underestimates the maximum accumulation in 2004/05, and the models tend to have less SWE than that observed in that second winter. An interesting feature of Fig. 4 is that the interquartile range in modeled SWE is less for the forested plots than for the open plots. This will partly be due to calibration, but the presence of a canopy decreases solar radiation and turbulent transport at the snow surface, so model spread resulting from uncertainties in partameterizations of snow albedo and sublimation will also be reduced.

Some previous intercomparisons of land surface process models have found that multimodel means performed better in comparison with observations than individual models (Frei et al. 2005; Guo et al. 2007). Because the SWE observations frequently lie outside the interquartile range of the simulations, it is clear from Fig. 4 that this is not the case for SnowMIP2. However, no single model or group of models emerged as performing consistently better than all of the other models for all simulations either.

A wide range of metrics are used in meteorology and hydrology for evaluating model outputs in comparison with observations, including average error, root-mean-square (rms) error, mean absolute error, correlation, and Nash–Sutcliffe efficiency. Figure 5 shows rms errors in modeled SWE, normalized by the standard deviation of the observations and ranked for every simulation; it should be noted that this ranking takes no account of uncertainties in the driving or evaluation data. Models that used the forest calibration data for the first year at each site are identified by solid circles, and those that did not are identified by open circles. As would be expected, the best simulations are for the calibration years at the forest sites by models that used the calibration data, although some uncalibrated models give good simulations and some calibrated simulations are poor by this measure; the calibration method was left open, and the models did not have to calibrate to minimize rms error. The poorest simulations, however, are for the Alptal and BERMS forest plots in the years for which calibration data were not provided, and the ranking is more mixed between calibrated and uncalibrated models. Open plot simulations, all of which are uncalibrated, generally have intermediate errors between the calibrated and uncalibrated forest simulations. Model calibration is clearly beneficial when the necessary data are available, but it appears that uncalibrated models tend to perform better for open sites than forested sites, and calibration against 1 yr of data at a site does not provide robust parameter values that can be transferred to other years.

Albedo measurements can be biased by snow on upward-looking radiometers following snowfall. To reduce this, individual measurements with outgoing shortwave radiation exceeding 90% of the incoming radiation were filtered out before calculating the daily albedos shown in Fig. 6. Albedos measured above the canopies at the forest sites only show a slight increase during the winter, and this is well represented by most models; indeed, some models use a fixed value for forest albedos, irrespective of snow cover. The high albedos observed while there was snow on the ground at the Alptal and BERMS open plots are also captured by the models, although there is a tendency for modeled albedos to decay faster than those observed between snowfalls; similar results were found in an intercomparison of snow albedo parametrizations by Pedersen and Winther (2005). As can be seen in Fig. 2, the "open" plot at Fraser Experimental Forest is in fact a regenerating clear cut, and there are sparse 2–4-m-tall trees within the downward-looking radiometer's field of view; snow measurements were made in open areas, but measured albedos are lower than might be expected for a snow-covered open plot when the trees have shed their intercepted snow. To allow for a more direct comparison, simulated albedos are reduced by averaging with a 30% snow-free fraction for the Fraser Experimental Forest open plot in Fig. 6.

Daily averages of effective surface temperatures, calculated from measurements of outgoing longwave radiation, are shown in Fig. 7, along with daily average air temperatures for comparison. As for albedo, simulated surface temperatures for the Fraser Experimental Forest open plot are combined with 30% fractions at canopy temperatures simulated for the forest plot. Compared with other variables considered here, the range in modeled surface temperatures is small, and the average of the model results compares well with observations. For rough forest surfaces, there is a strong aerodynamic coupling between canopy and air temperatures. Canopy surfaces are generally warmer than the air during daytime and colder at night, so differences in daily average temperatures are smaller than instantaneous differences. For open snow surfaces, the aerodynamic coupling to the atmosphere

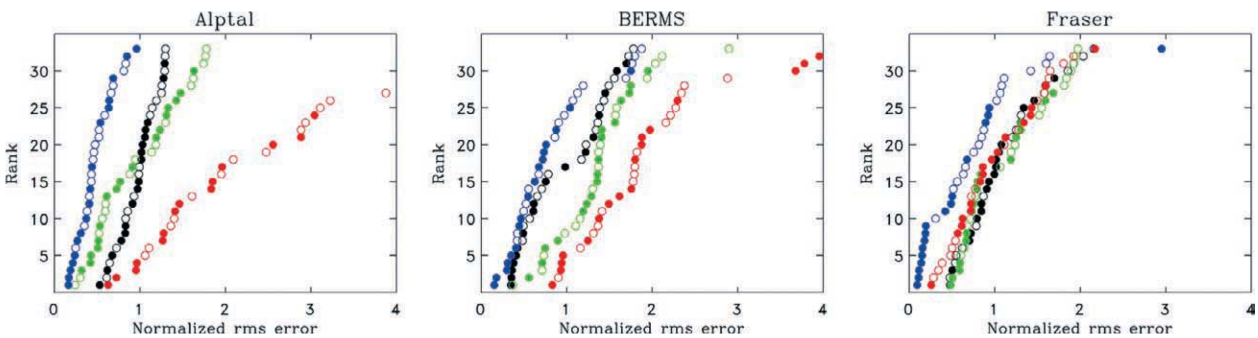

Fig. 5. Normalized and ranked rms errors for SWE simulations at forest sites in the years for which calibration data were available (blue circles) or not available (red circles) and open sites in the forest calibration years (black circles) or noncalibration years (green circles). Filled circles are for simulations with models that used the calibration data when they were available and open circles are those that did not.

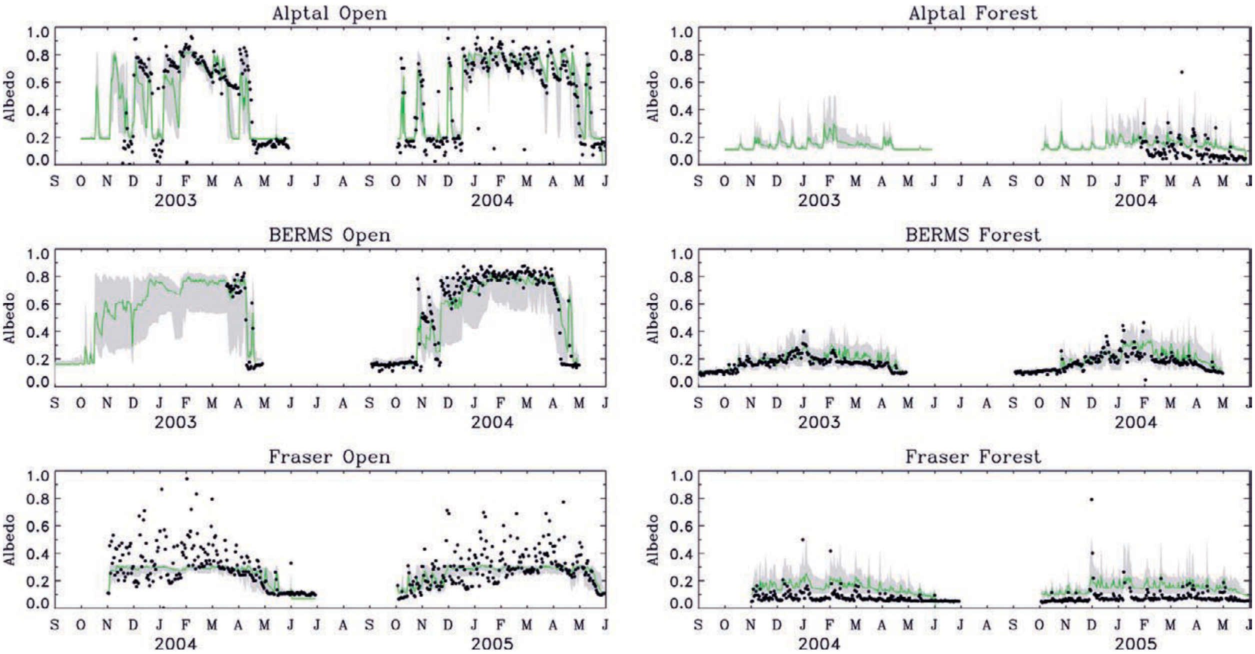

Fig. 6. Same as Fig. 4, but for observed and modeled albedos.

is less strong, and the surface temperature cannot exceed 0°C; surface temperatures are often lower than air temperatures for the open plots in Fig. 7.

Soil temperatures were measured at a depth of 20 cm in the Alptal forest plot and at several depths in the forested and open plots at BERMS and Fraser Experimental Forest. The soil at Alptal is a very wet clay that strongly dampens temperature variations. Despite cold air temperatures, soil temperatures rarely fall below 0°C at Alptal and Fraser Experimental Forest or below −5°C at the BERMS forest plot. Temperatures for the surface soil layer of each model were requested in SnowMIP2, but soil temperature profiles were not; the results are not directly comparable, because the model surface layers range in thickness from an infinitesimal skin to 60 cm.

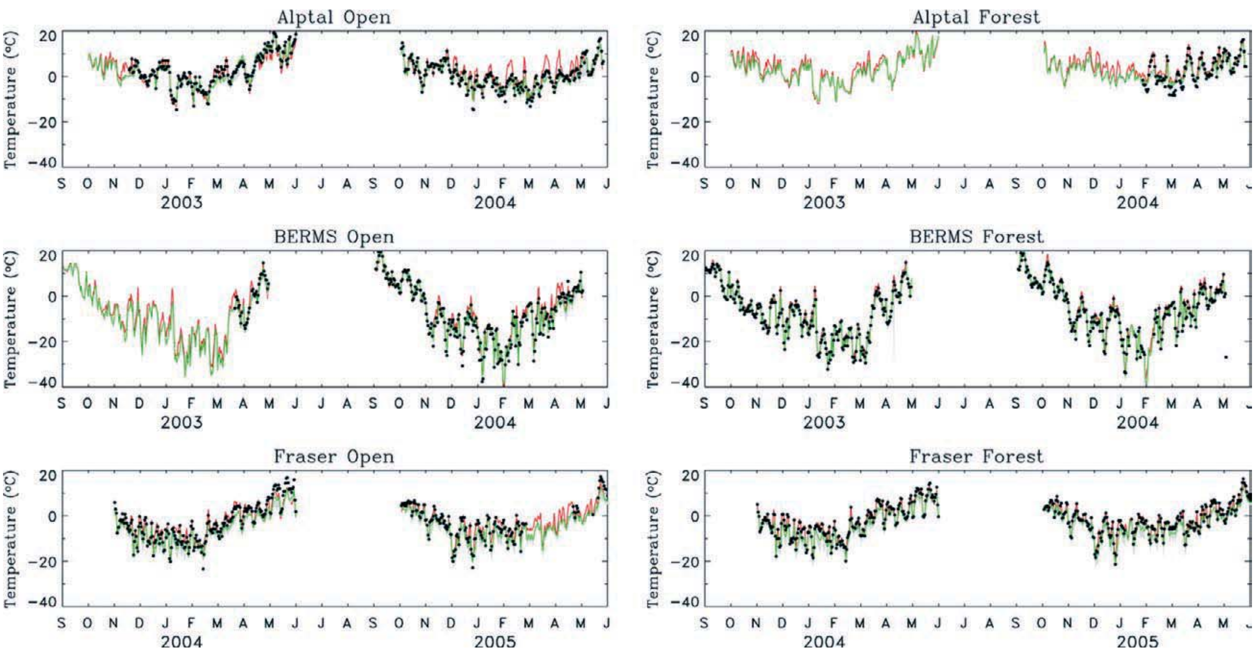

Fig. 7. Same as Fig. 4, but for observed and modeled surface temperatures. Red lines show daily average air temperatures.

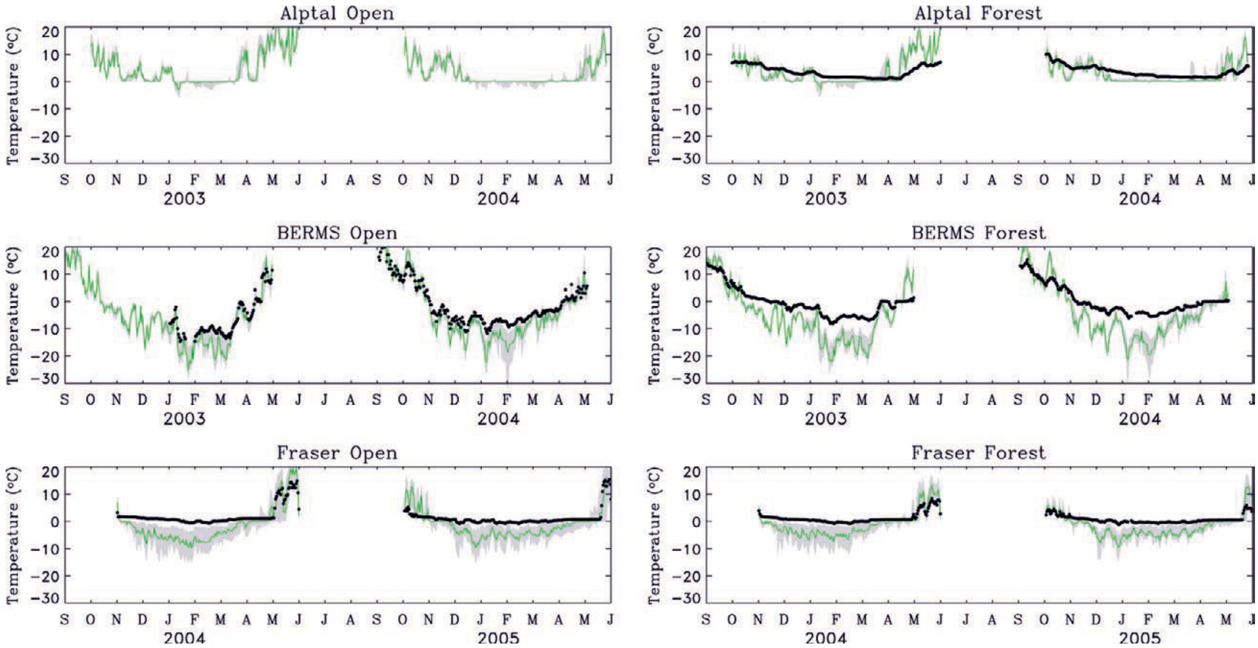

FIG. 8. Same as Fig. 4, but for observed and modeled soil temperatures.

The comparison with observations in Fig. 8 should be viewed cautiously, therefore, but suggests that the models tend to somewhat underestimate winter soil temperatures at BERMS, particularly for the forested plot, where soil temperatures do not fall as low as at the open plot. This is despite parametrizations of soil freezing, which slows the rate of cooling by the release of latent heat, being included in all but 2 of the 26 models that returned soil temperatures for SnowMIP2. Larger cold biases in winter soil temperatures were found for models that did not include soil freezing in the PILPS 2d intercomparison (Luo et al. 2003).

CONCLUSIONS. Results were submitted to SnowMIP2 from 33 models for simulations of surface energy and mass balances at five paired open and forested sites, three of which are presented here. The models generally predict the duration of snow cover quite well but show broad ranges in their simulations of maximum snow accumulation, particularly at warmer sites and during warmer winters, and differences between open and forested plots are underestimated on average. These uncertainties will have consequences for hydrological applications where the timing and amount of snowmelt runoff are important. Calibration improves the simulations for forest sites, but the availability of 1 yr of calibration data does not ensure good simulations for a subsequent year. There is very little consistency in model performance between sites and years, so no "best" model can be identified. Conversely, and contrary to experience in some previous land surface model intercomparisons, systematic biases for particular sites and years mean that the multimodel mean does not perform consistently better than the individual models. Uncertainties in inputs of snowfall can account for some of the systematic model errors.

For surface energy balance calculations, required in coupled atmospheric modeling applications, the first-order control of snow being present or absent on the surface is more important than the exact amount of snow. The large differences in albedo and surface temperature between forested and open sites, and between snow-covered and snow-free surfaces, are generally modeled quite well. On the whole, SnowMIP2 simulations do not show the large positive biases in albedo over snow-covered forests found by Roesch (2006) for IPCC AR4 simulations, but these could also result from uncertainties in the specification of vegetation characteristics for global models.

The SnowMIP2 models tend to predict winter soil temperatures that are too low, particularly for the cold air temperatures and shallow snow at the BERMS sites. This will be problematic for simulations of biological processes controlled by temperature in soils under snow. Uncertainties remain in the modeling of physical and ecosystem processes in winter, and measurements of winter processes for development and testing of models remain sparse in the boreal zone. One of the key current aims in ecosystem modeling is to obtain better estimates of carbon fluxes between vegetated land surfaces and the atmosphere. Effective representations of soil freeze–thaw cycles, thermal properties, and moisture content, both during and following snow cover, are key to this for seasonally snow-covered boreal ecosystems. Accurate simulations of forest snow and soil processes are therefore critical for both ecosystem and climate modeling (Zhang et al. 2008). Interdisciplinary approaches combining expertise from meteorology, soil physics, ecology, and hydrology are required.

The results of SnowMIP2 show that many current land surface models represent a sufficient range of processes that can be calibrated to reproduce the mass balance of forest snow packs well while simultaneously providing reasonable estimates of canopy albedos and temperatures that are essential for simulating the surface energy balance. It appears, however, that uncertainties in parameter selection overwhelm deficiencies in model structure when calibration data are not available. Drawing on data assimilation techniques, sensitivity to data error, model complexity, calibration, and parameter transferability could be assessed with ensembles of perturbed simulations for longer periods and more sites, but such an investigation would be better conducted with a small number of representative models rather than the large number of models that participated in SnowMIP2. A further challenge is to evaluate the performance of models at the large scales on which they are typically applied; this should be approached by combining modeling with remote sensing of forest structure and snow properties.

ACKNOWLEDGMENTS. This work was made possible by the enthusiastic participation of the modeling groups acknowledged in Table 1. Additional field data were provided by Kazuyoshi Suzuki, Tomoyoski Hirota, Jukka Pumpanen, and Timo Vessala. We thank Drew Slater and two anonymous reviewers for their comments on this paper. Coordination of SnowMIP2 was supported by a grant from the U.K. Natural Environment Research Council.

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